M. Marentic built much of the equipment used in the capacitance measurements. I am indebted to W. J. Coates for suggesting the use of quarter-wave stubs in the capacitance measurement.

REFERENCES

[1] L. F. Weber, "Discharge physics studies for the AC plasma display panel," *Conference Record, 1974 Conference on Display Devices and Systems*, IEEE Publication 74CH0892-OED, pp. 20–26.
[2] L. F. Weber, "Discharge dynamics of the AC plasma display panel," Coordinated Science Lab., University of Illinois, Urbana, IL, Report R-687, Aug. 1975. Available NTIS #AD-A017 300/5GA.
[3] R. H. Huddlestone and S. L. Leonard, *Plasma Diagnostic Techniques*. New York: Academic Press, 1965.
[4] H. J. Oskam, "Microwave investigation of disintegrating gaseous discharge plasmas," *Philips Res. Repts.*, vol. 13, pp. 335–457, 1958.
[5] C. L. Chen, "Electron collisions in neon plasma," *Physical Review* vol. 135, no. 3A, p. A627, 1964.
[6] L. F. Weber, "Measurement of wall charge and capacitance variation for a single cell in the AC plasma display panel," this issue, pp. 864–869.

Measurement of Wall Charge and Capacitance Variation for a Single Cell in AC Plasma Display Panel

LARRY F. WEBER, MEMBER, IEEE

***Abstract*—Real-time dynamic measurements are performed on a single cell in a standard commercially available large plasma panel. The measurements determine cell response to variations in address pulses, sustain waveforms, or priming from neighboring cells. The wall-charge measurement indicates the internal dielectric surface charge and the capacitance measurement indicates the existence of a plasma in the gas volume. These measurements have shown that neighboring on cells can cause a large wall-charge transfer in off cells that results in reduced write and sustain voltage margins. Direct wall-charge measurements allows use of a simple technique for determination of the voltage transfer curve of the plasma cell which greatly aids device characterization. The capacitance measurement has shown that a plasma exists in commercial MgO panels for 10–15 µs after the discharge-current peak. The capacitance and wall-charge measurements can be combined to give simultaneous real-time results.**

I. INTRODUCTION

CHARACTERIZATION of the ac plasma display cell has always been difficult. This is principally due to the small number of measurements that are readily applicable to this device. For instance, direct measurement of the voltage across the gas at various times is not possible because such a measurement would strongly perturb the discharge activity, which is coupled to the outside world by a very small capacitance of 10^{-2} pF. Thus one is forced to guess at this voltage by measurement of other quantities such as discharge light or firing voltages.

This paper discusses measurement of two signals that should be a great aid to device characterization. Both measurements are performable on single cells in standard commercially available large panels. By carefully measuring the charge coming out of a panel electrode due to a single-cell discharge, a signal that is proportional to the wall voltage is readily obtained. Also, the time-varying capacitance of a single cell can be measured to yield information about the charge trapped in the gas volume. The signal-to-noise ratios of both measurements are sufficient to allow real-time determination without averaging.

II. WALL-CHARGE MEASUREMENT

Fig. 1 shows typical wall-charge data measured with the circuit of Fig. 2. The lower trace shows the Y-axis sustain voltage in which a single 20-V write pulse was introduced. The upper trace shows the resulting wall voltage. The cell was initially in the off state with the sustain voltage set at 107 V. Since this is very close to the firing voltage of this cell, the cell went on due to the application of the small write pulse. These data demonstrate the growth to equilibrium for a single event in a single cell.

The basic technique used to measure the wall voltage is the old idea of placing a capacitor in series with the plasma cell in order to integrate the discharge current and thus yield a signal proportional to the wall voltage. The

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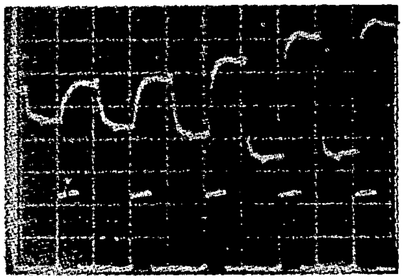

Fig. 1. Wall charge (above) and the Y-axis component of the sustain voltage (below) for a growing series of discharges in a single cell. The time scale is 10 μs/div and the sustain voltage scale is 50 V/div.

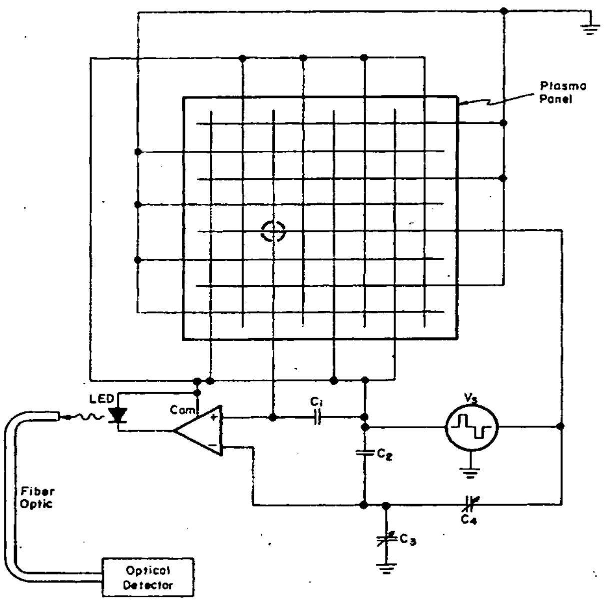

Fig. 2. Circuit used to measure wall charge in single cell.

major difficulties with this technique are that the changing sustain voltage induces a very large displacement current through the cell capacitance that is much larger than the discharge current. Also, if the panel is sustained in the usual manner, with a sustain generator on each axis, then the current-integrating capacitor will be floating on the changing sustain voltage, making it difficult to measure the small wall-voltage signal.

In the circuit of Fig. 2, the discharge in the circled cell will cause charge to flow through the integrating capacitor C_1, which causes a voltage which is proportional to the wall charge to appear across C_1. This voltage is detected by the differential amplifier that drives an optical isolator made of a light emitting diode, a 30-cm-long fiber optic, and an optical detector. The optical isolator allows the differential amplifier to float on the changing sustain voltage, and thus it relieves the amplifier of an unusually high common-mode rejection ratio requirement. The commercially available optical isolators are not suitable for this purpose because the capacitance between the LED and the optical detector causes very large noise spikes when the sustain voltage changes.

The capacitor C_1 is charged by the discharge current and also by the displacement current induced by the changing sustain voltage. The displacement current produces an unwanted voltage across C_1 that is usually very much greater than the wall-voltage signal. The displacement charge is balanced out by connecting the negative terminal of the differential amplifier to a charge-compensating network comprising C_2, C_3, and C_4. C_2 is usually of the same value as C_1, which is typically 100 pF. C_3 and C_4 are adjusted until they equal to capacitances of the vertical measured cell electrode both to ground and to the cell horizontal electrode. When properly balanced, the output of the optical detector remains unchanged when the cell is off and the sustain voltage is applied.

The input impedance of the differential amplifier must be very large so that the wall charge will not leak off C_1 during the time of the measurement. It must not be too high or else the amplifier will saturate due to the large dc voltages that can build up. The value used here was 22 MΩ.

Since the changing sustain voltage of typically 100 V is so much greater than the millivolt-sized signal across C_1, the selection of the circuit components is critical to maintaining the displacement-charge balance. The capacitors must be very linear and have low leakage. The linearity requirement excluded the use of ceramic capacitors. Also, air variables can change their capacitance upon application of the sustain voltage due to the force that can change the distance between the plates. Silver mica capacitors have the necessary linearity to be used for C_1 and C_2 and quartz-piston variable capacitors have the necessary mechanical rigidity and low leakage for C_3 and C_4. It is very important to use quartz instead of glass-piston capacitors since the motion of ions in the glass can cause a considerable conductivity that leads to a very noisy signal.

Examination of the signal and impedance levels involved in this measurement show that a very significant unbalance of the circuit will occur if one lead of a 1000-MΩ resistor is connected to either input of the differential amplifier. This is due to the significant amount of charge, induced by the changing sustain voltage, that flows through the resistor to the stray capacitance of the unconnected resistor lead. Thus any high resistances can cause severe problems. Things like wire insulation can doom this measurement to failure. Teflon insulation is the only one found that has worked satisfactorily.

The humidity of the room can cause significant problems. On one humid day it was found that the quartz piston capacitors were unbalancing the circuit by means of the surface conductivity of the quartz. The surface conductivity of quartz can increase 4 or more orders of magnitude [1] when the humidity increases from 40 to 80 percent. The solution was to drive off the water by heating the capacitors with a properly placed resistor.

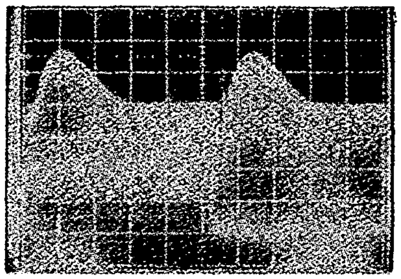

Fig. 3. Sustain-voltage waveform and 30-MHz RF envelope showing the capacitance variation of a single cell. The time scale is 5 μs/div and the voltage scale is 50 V/div.

The conductivity of the plasma panel substrate glass can also make things difficult. The major problem is surface and volume conductivity between the vertical electrode intersecting the measured cell in Fig. 2 and the adjacent parallel electrodes. This conductivity problem is minimized in Fig. 2 by connecting all parallel electrodes to the sustainer, which is at very nearly the same potential as the vertical electrode intersecting the measured cell. When all other vertical electrodes were grounded instead of connecting them to the sustainer, the conductivity of the panel glass became very troublesome since nearly the full sustain voltage appears between the electrode intersecting the measured cell and the adjacent parallel electrodes.

III. Capacitance Measurement

Previous work [2]–[4] has shown that the capacitance of plasma cells has a time-varying component due to a plasma that is trapped in the gas volume for many microseconds after the discharge peak. The nature of this plasma and its effects on the capacitance are discussed extensively in the preceding paper in this issue [4].

Fig. 3 shows the capacitance variation for a single cell in an 128 × 128, 60 lpi experimental MgO panel made by Owens-Illinois. This cell would fire at 107 V and would extinguish at 89 V with a 50-percent duty-factor, return-to-zero sustain waveform. The data shown in Fig. 3 were taken with V_s = 96 V, which is in the mid-range of operation. These data show the Y-axis sustain waveform and the 30-MHz RF envelope that indicates the capacitance. The envelope increases as the capacitance increases. Clearly the capacitance is still changing for longer than 10 μs after the discharge peak; and thus the plasma exists for long times relative to the sustain cycle. This is very similar to the behavior noticed in the previous work for a large number of cells connected in parallel [2]–[4]. The duration of the plasma is strongly dependent on the sustain voltage. In general, the plasma lasts longer for larger voltage. Near the minimum sustain voltage, the plasma is hardly noticeable. Referring to Fig. 1 of the preceding paper [4], the value of the neutral capacitance C_0 of a typical plasma cell is on the order of 10^{-3} pF. Depending on various conditions, the value of the peak cell capacitance C_p has been measured to be from 5 to 10 times greater than C_0 [3], [4]. When this cell is in a typical plasma panel, it is placed in parallel with the electrode capacitance of at least 10 pF. Thus to measure the variation of capacitance of a single cell in a plasma panel, it is necessary to be able to observe a capacitance variation of better than one part in 10^4.

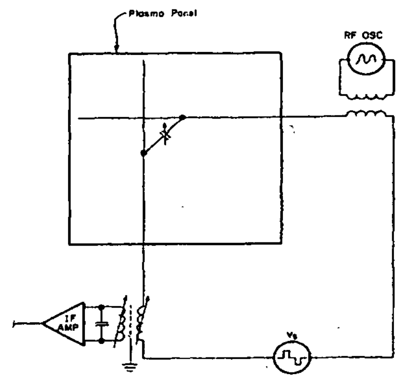

Fig. 4. Circuit used to measure the capacitance variation of a single cell.

The data of Fig. 3 were taken with the circuit shown in Fig. 4. The voltage from a 30-MHz oscillator is coupled to the horizontal panel electrode with a suitable transformer. The p-p RF voltage is restricted to 1 V or less so that it does not significantly alter the operation of the cell. The variation in coupling to the vertical electrode due to the cell capacitance change is measured by a high-input-impedance wide-band amplifier that is coupled to the electrode with a tuned transformer. A 30-MHz radar IF strip worked very well for the required amplifier. The primary of the transformer is a slug-tuned coil that is adjusted to resonate with the electrode capacitance at 30 MHz. Similarly, the secondary winding is also made to resonate at 30 MHz.

Since both windings are resonant, only very loose coupling is necessary to achieve good results; and therefore the two windings can be spaced far apart. This is convenient since it reduces the capacitance between the two windings and allows a simple Faraday shield to be placed between them. The shield is necessary to keep the sustain-voltage-induced displacement currents from flowing through the secondary coil, which is at ground potential. These currents cause an undesirable ringing that easily obscures the capacitance variation if the shield is not used.

A second advantage of the resonant structure is that it increases the effective impedance of the panel electrode at the RF frequency. Thus the capacitance variation of the cell will cause a larger RF voltage change across the resonators than it would across the electrode capacitance alone. The disadvantage is that some time response is sacrificed in the resonant circuit, but this has not been a serious problem since 30 MHz is considerably faster than the typical capacitance variation.

Not shown in Fig. 4 are various shields and 30-MHz traps that are necessary to keep the 30-MHz signals from reaching the nonlinear components of the sustain-pulse generator. This can introduce noise spikes and falsely modulate the desired signal. These modifications are consistent with good RF practice.

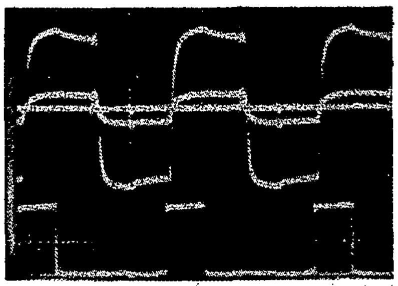

Fig. 5. Y-axis sustain waveform and 3 wall-charge traces showing the effects of neighboring cells on an off cell. The time scale is 5 μs/div and the sustain-voltage scale is 50 V/div.

IV. Measurement Results

A. Neighboring-Cell Effects

A number of interesting results have been achieved through the use of these measurement techniques. Fig. 5 shows the effects of neighboring cells on wall charge. The lower trace is the sustain voltage on the y axis only. The upper three traces show the wall charge for three different conditions. The straight line wall-charge trace is for all cells in the panel in the off state. The trace that goes one half division either side of center is for the measured cell in the off state but with the 2 cells on either side of it in the on state. The largest-amplitude trace is for the measured cell in the on state. It is very interesting to note that the two neighboring cells cause a very significant amount of wall-charge transfer in the off cell. This data is for the MgO panel described above with a 50-percent-duty-factor sustain waveform set at 100 V. This was 7 V below the firing voltage for this cell. This effect is also seen in Fig. 1 as a charge transfer occurring before the write pulse when the cell was in the off state. This occurred because the two neighboring cells in Fig. 1 were in the on state.

The amount of charge transfer of the off cell with the two nearest neighbors in the on state depends strongly on the sustain-voltage setting. As the sustain voltage is brought near the firing voltage, the charge transfer of the off cell will nearly double that shown in Fig. 5. This measurement technique allows cells to be in the on state along the horizontal electrode of Fig. 2, although cells in the on state along the vertical electrode of the measured cell would interfere with the wall charge of the measured cell. Thus, unfortunately, it was not possible to measure the wall charge transfer for an off cell surrounded by 4 on cells. It would probably be considerably larger than that shown in Fig. 5. It has also been observed that the charge transfer for only one neighbor in the on state seems to be about half of that for two neighbors on.

These measurements have great significance because they explain why it is difficult to write an off cell that is surrounded by on cells [5]. The wall-voltage transfer of the off cell in this situation has a magnitude that subtracts from the voltage across the gas at the time of the write discharge, thus making it harder to write that cell. Peter Ngo has measured this effect by noting the variation in write-pulse voltage needed to turn an off cell on as a function of the number and distance of the neighboring on cells [6]. He shows that the required write voltage with the neighbors on is 15 V greater than with them off.

The wall voltage transfer of the off cell shown in Fig. 5 will also cause the firing voltage of that off cell to be reduced since the wall voltage will add to the sustain voltage to increase the electric field across the cell. This effect has been used to great advantage for shifting images in plasma panels [7], [8], and for reducing the number of drive circuits by means of discharge logic [9].

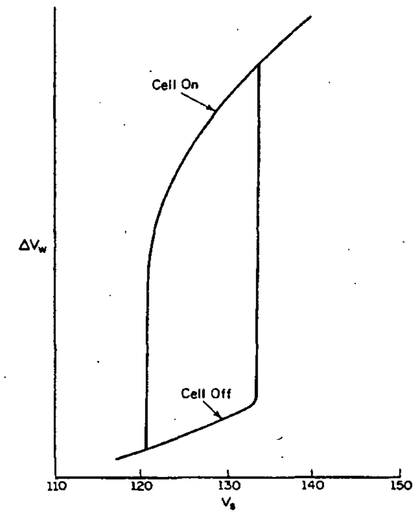

Fig. 6. Measured hysteresis curve for a single cell in a PbO 60-lpi 512 × 512 panel filled with 600 torr Ne + 0.1-percent Ar.

B. Reverse Discharge

Another interesting result seen in Fig. 5 is that when the sustainer falls to zero there is a significant reverse discharge in the on cell that causes the wall voltage to decrease. This reverse discharge is strongly dependent on the sustain voltage level. It is generally stronger for the larger voltages. Near the minimum sustain voltage it may be unobservable, but it is always seen near the firing voltage. This reverse discharge has been observed before, and it is predicted by computer calculations [3]. It is caused by the sweep-out of the plasma by the fall of the sustainer. This theory is supported by the fact that the reverse discharge always disappears when the plasma is swept out by other means such as small voltage pulses introduced before the sustain-voltage fall [4].

C. Hysteresis Curve

By measuring the amplitude of the wall-charge transfer as a function of the applied sustain voltage, one obtains the hysteresis curve of that cell. A typical hysteresis curve, taken on a PbO panel filled with 600 torr Ne + 0.1-percent Ar, is shown in Fig. 6. This cell had its two nearest neighbors in the on state; and thus there was a significant amount of charge transfer while the cell was off, similar to that seen in Fig. 5.

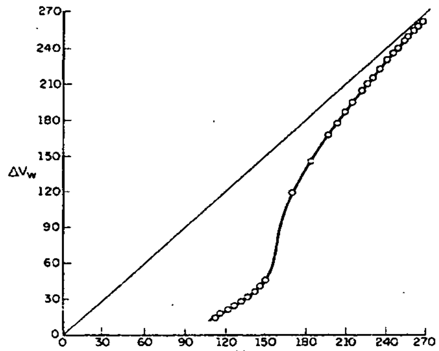

Fig. 7. Voltage transfer curve derived from the data of Fig. 6, showing the change in wall voltage ΔV_w as a function of the initial voltage across the gas V_c.

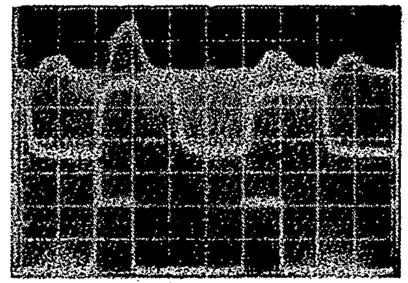

Fig. 8. The Y-axis sustain waveform in the lower trace, the wall charge variation in the middle, and the RF envelope showing the capacitance variation in the upper trace. The time scale is 5 μs/div and the sustain-voltage scale is 50 V/div. This is for the MgO panel with $V_s = 100$ V. Five discharges are shown. The period between discharges is 10 μs. A 50-V 500-ns perturbing pulse is added to the normal sustain waveform at the beginning of the second discharge which occurs at 10 μs after the start of the trace.

The ΔV_w axis is not scaled because of the uncertainties of the relationship between the actual wall voltage and the charge that flows out of the electrode. This is because the exact dielectric-glass thickness of the panel is not known. Also, it is not clear how to treat the fringing-field problem for the plasma discharge or the possible variations in discharge area with changing sustain voltage. However, the proportionality constant relating the wall voltage and the measured charge can be estimated within better than a factor of 2 by constraints on the plasma cell operation. The upper constraint is that the wall-voltage transfer cannot be greater than the initial voltage across the gap. The lower constraint is that the hysteresis curve should yield a monotonic voltage-transfer curve.

D. Voltage Transfer Curve

Once the above-mentioned proportionality constant is chosen, a simple mathematical transformation yields the voltage transfer curve [10], [11]. The transfer curve for the data of Fig. 6 is seen in Fig. 7. This is the fundamental electrical characteristic curve of this device. Unfortunately, it has not been widely measured because of the tedious procedure previously required. The technique presented here is relatively straightforward since the hysteresis curve seen in Fig. 6 was quickly plotted on a chart recorder. It should be quite easy to design a curve tracer for plasma panels. Unfortunately, since the hysteresis curve of Fig. 6 is taken while the cells are in a stable steady state, it is not possible to derive the transfer curve for the unstable points where the slope of the curve is greater than 2. Thus these points are not shown in Fig. 7 but their position is estimated by the solid line. It should be possible to derive the unstable points from a discharge series in transition between stable states, e.g., from data such as is seen in Fig. 1.

V. Combining Both Measurements

It is quite useful to use the wall-charge measurements in combination with the capacitance measurements. There is no reason why the circuits of Figs. 2 and 4 cannot be combined if good RF techniques are maintained and no lossy materials are used. Fig. 8 shows the Y-axis component of the sustainer, the wall-charge variation, and the capacitance envelope for a series of five discharges. On the second discharge, a 500-ns 50-V pulse was added to the leading edge of the Y-axis sustainer. This caused a larger than normal amount of wall charge to be transferred; but more significantly, it caused the capacitance to increase by three times the steady-state capacitance change. When the sustainer returned to zero, the plasma was swept out of the volume; and the capacitance returned to the neutral level. Because of the greater amount of plasma, the reverse-discharge wall-voltage change was greater than the steady-state value. For some unexplained reason, the third discharge was weaker than normal, and it did not create any plasma. The fourth discharge created slightly more than the equilibrium amount of plasma, and the fifth discharge was returned to the equilibrium value.

The important point to be seen from these data is the much more complete picture of this discharge sequence that is given when both the wall charge and the volume charge can be measured.

VI. Conclusion

These measurement techniques should significantly increase the development engineer's ability to characterize this device. He can now directly measure the key parameter that indicates the device operation—the wall charge. Thus he can easily observe and record how the wall charge is affected by various perturbing forces. This should go a long way toward eliminating the vague electrical specifications that are presently in use. Work is continuing at the University of Illinois toward building a curve tracer for plasma panels that will rapidly give the voltage transfer curve of a panel at the press of a button. This will be accomplished by placing the sustain-voltage generator and wall-charge measurement under computer control.

Direct wall-charge measurement should be to the plasma-panel research engineer what the graphics display is to the numerical analyst. The numerical analyst can observe all of his computed results by means of pages of numbers on a alpha-numerics terminal, or he can use the

graphics display to plot curves of the data. The graphics approach is less tedious and thus allows much more data to be reviewed. But just as important is the fact that the graphics allows the analyst to quickly recognize new patterns in his data. Similarly, the plasma-panel research engineer's job of determining the wall voltage can be done by indirect means such as observing light output as a function of various perturbing voltage pulses. The voltage values arrived at after such a measurement must then be mathematically transformed or plotted to achieve useful results. A good example of this technique is the work of Peter Ngo in determining the effects of neighboring discharges on the wall voltage of an off cell [6]. The results are achieved only after the tedious process is completed. However, by the direct wall charge measurement technique, similar results were achieved in the work presented here by simply observing the wall charge as seen in Fig. 5.

The equipment required for wall-charge measurement is relatively simple. This is not to say that there is not a great deal of art in designing and setting up the required circuits. However once the art is mastered, the setup is almost routine. To date three different wall-charge-measurement systems using the circuits of Fig. 2 have been set up and operated satisfactorily using three different-geometry plasma panel configurations. Two of these systems were used with Owens-Illinois 512-60 panels. Based on the experience gained in building the first two, the third system worked the first time it was tested.

The single-cell capacitance measurements are currently of less value to the development engineer than are those of the wall charge. These capacitance measurements are also more difficult to set up since careful RF shielding is usually required. However, the research engineer will want to use the capacitance measurement in conjunction with the wall-charge measurement because of its value in determining the presence of plasma. Prior to the development of these techniques, there was no simple way to determine the presence of plasma. Thus the ability to detect it should lead to discovery of a number of interesting effects. For example, the reaction of the plasma to the sustain waveform seen in Fig. 8 is inexplicable by current theory. Thus there exists an opportunity for a better theoretical understanding of this device.

ACKNOWLEDGMENT

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REFERENCES

[1] E. M. Guyer, "Electrical Glass," *Proc. IRE*, vol. 32, p. 743, 1944.
[2] L. F. Weber, "Discharge physics studies for the ac plasma display panel," in *Conf. Rec., 1974 Conference on Display Devices and Systems*, IEEE Publication 74CH0892-OED, pp. 20–26.
[3] L. F. Weber, "Discharge dynamics of the AC plasma display panel," Report R-687, Coordinated Science Lab., University of Illinois, Urbana, IL, August 1975. Available NTIS #AD-A017 300/5GA.
[4] L. F. Weber, "Measurement of a plasma in the ac plasma display panel using rf capacitance and microwave techniques," this issue, pp. 000–000.
[5] N. Nakayama and S. Andoh, "Design of a plasma display panel," in *Proc. SID*, vol. 13, 1972, pp. 61–66.
[6] P. D. T. Ngo, "Charge spreading and its effect on ac plasma panel operating margins," this issue, pp. 000–000.
[7] S. Umeda and T. Hirose, "Self-Shift Plasma Display," in *Dig. Papers, 1972 SID International Symposium*, pp. 36–37. May 1972,
[8] L. M. Jones and R. L. Johnson, "A parallel self-shift technique for plasma display/memory panels," *IEEE Trans. Electron Devices*, vol. ED-22, pp. 235–239, May 1975.
[9] J. D. Schermerhorn and J. W. V. Miller, "Discharge-logic drive schemes," *IEEE Trans. Electron Devices*, vol. ED-22, pp. 669–673, Sept. 1975.
[10] H. G. Slottow and W. D. Petty, "Stability of discharge series in the plasma display panel," *IEEE Trans. Electron Devices*, vol. ED-18, p. 650, September 1971.
[11] H. G. Slottow, "The voltage transfer curve and stability criteria in the theory of the ac plasma display," this issue, pp. 848–852.